Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

K.-I. Nishikawa (*NSSTC/UAH*),

J. Niemiec (*INP, PAN*), M. Medvedev (*U. of Kansas*), B. Zhang (*UNLV*), P. Hardee (*U. of Alabama, Tuscaloosa*), Y. Mizuno (*NSSTC/UAH*), Å Nordlund, J. Frederiksen, (*Niels Bohr Inst.*), H. Sol (*Observatore de Paris-Meudon*), M. Pohl (*ISU*), D. H. Hartmann (*Clemson U.*), G.J. Fishman (*NASA/MSFC*)

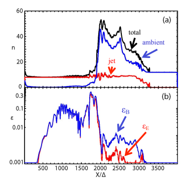
Recent PIC simulations of relativistic electron-positron (electro-ion) jets injected into a stationary medium show that particle acceleration occurs within the downstream jet. The Weibel instability is responsible for generating and amplifying highly nonuniform, small-scale magnetic fields. These magnetic fields contribute to the electron's transverse deflection behind the jet head. The radiation from deflected electrons has different properties than synchrotron radiation which is calculated in a uniform magnetic field. This radiation obtained self-consistently may be important to understanding the complex time evolution and/or spectral structure in gamma-ray bursts, relativistic jets, and supernova remnants. New recent calculation of spectra with various different Lorentz factors of jets and initial magnetic fields. New spectrum based on small scale simulations is presented.

Key Scientific questions

- **How do shocks in relativistic jets evolve?**
- **How are particles accelerated?**
- **What are the dominant radiation processes?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock fronts and transition regions?**
- **How do shocks in relativistic jets evolve under various ambient plasma and magnetic fields?**
- **How do magnetic fields generated by the Weibel instability contribute to radiation?**

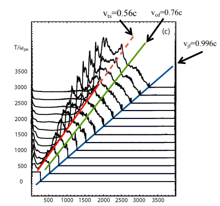
-- for some answers see Nishikawa et al. 2006, ApJ, 642, 1267 Ramirez-Ruiz, Nishikawa & Hededal, 2007, ApJ, 671, 1877 Nishikawa et al. 2009, ApJ, 698, L10 --

Shock formation, forward shock, reverse shock



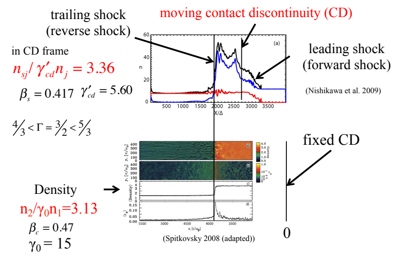
(a) electron density and (b) electromagnetic field energy (ε_B, ε_E) divided by the total kinetic energy at t = 3250ω_{pe}^{-1}

(Nishikawa et al. ApJ, 698, L10, 2009)



Time evolution of the total electron density. The velocity of jet front is nearly c, the predicted contact discontinuity speed is 0.76c, and the velocity of trailing shock is 0.56c.

Shock velocity and structure based on 1-D HD analysis



Present theory of Synchrotron radiation

- Fermi acceleration (Monte Carlo simulations are not self-consistent; particles are crossing at the shock surface many times and accelerated, the strength of turbulent magnetic fields are assumed), New simulations show Fermi acceleration (Spitkovsky 2008)
- The strength of magnetic fields is assumed based on the equipartition (magnetic field is similar to the thermal energy) (ε_B)
- The density of accelerated electrons are assumed by the power law ($F(\gamma) = \gamma^{-p}$; p = 2.2?) (ε_e)
- Synchrotron emission is calculated based on p and ε_B
- There are many assumptions in this calculation

Self-consistent calculation of radiation

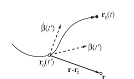
- Electrons are accelerated by the electromagnetic field generated by the Weibel instability (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated by the particle trajectory in the self-consistent magnetic field
- This calculation include Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
- Some synchrotron radiation from electron is reported (Nishikawa et al. 2008 (astro-ph/ 0801.4390;0802.2558))

Radiation from collisionless shock

To obtain a spectrum, "just" integrate:

$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3}\left|\int_{-\infty}^{\infty}\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^2}e^{i\omega(t'-\mathbf{n}\cdot\mathbf{r}_0(t')/c)}dt'\right|^2$$

where $\mathbf{r}_0$ is the position, $\boldsymbol{\beta}$ the velocity and $\dot{\boldsymbol{\beta}}$ the acceleration



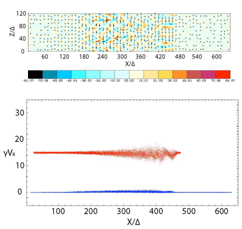
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)

Jitter radiation from electrons by tracing trajectories self-consistently

using a small simulation system initial setup for jitter radiation

select electrons (12,150) in jet and ambient



15,000 steps

final condition for jitter radiation

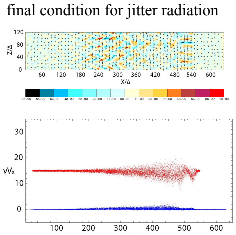
dt = 0.005ω_{pe}

ω_n = 100

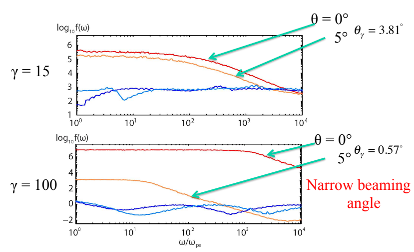
θ_n = 2

Δxjet = 75Δ

Δt_{jitt} = 75ω_{pe}



Calculated spectra for jet electrons and ambient electrons

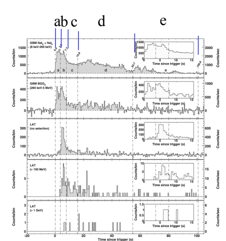


Spectra obtained from jet and ambient electrons for the two viewing angles for γ = 15 (upper) and γ = 100 (lower). Spectra with jet electrons are shown in red (0°) and orange (5°). Spectra from ambient electrons show the lowest levels by blue (0°)andlightblue (5°). It is noted that in the case with γ = 100 spectrum is extended in the higher frequency. However, the spectrum with viewing angle 5° is greatly decreased in particular in the high frequency due to the narrow beaming angle.

(Nishikawa et al. 2009 (arXiv:0912.1583))

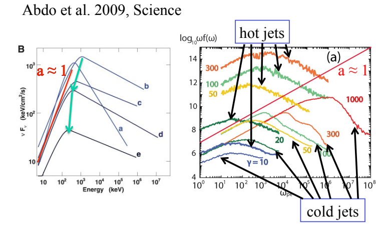
Observations and numerical spectrum

GRB 080916C



Time evolution of spectra from prompt emission to aftergrow, which would depend on plasma conditions such as jet electron Lorentz factor, particle acceleration, magnetic field strength and turbulence.

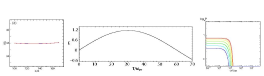
Abdo et al. 2009, Science



Nishikawa et al. 2011

Case D

γ = 7.11



Spectra obtained from jet and ambient electrons for the two viewing angles. Spectra with jet electrons are shown in red (0°) and orange (5°). Spectra from ambient electrons show the lowest levels by blue (0°) and light blue (5°).

Comparing with the spectrum for Bremsstrahlung with γ=7.11 (below), the spectra have more high frequency components. This is caused by the weak turbulent magnetic fields generated by the Weibel instability.

(Nishikawa et al. 2009 arXiv:0906.5018)

Results

- **The Weibel instability creates filamented currents and density structure along the propagation axis of the jet.**
- **The growth rate of the Weibel instability depends on the Lorentz factor, composition, and strength and direction of ambient B fields.**
- **The electron-ion ambient enhances the generated magnetic fields with the excitation ion Weibel instability.**
- **This enhanced magnetic field with electron-ion ambient plasma may be an origin of large upstream magnetic fields in GRB shocks.**
- **In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.**
- **Spectra from two electrons are calculated for different condtions.**
- **The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).**
- **New numerical approach of calculating radiation from electrons based on simulations self-consistently provides more realistic spectra including jitter radiation.**

Future plans

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics using the codes with MPI (Nishikawa et al. 2009).**
- **Radiation will be calculated in a self-consistent way using larger simulation systems (Nishikawa et al. astro-ph/0912.1583).**
- **Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability.**
- **Investigate radiation processes from the accelerated electrons and compare with observations (GRBs, SNRs, AGNs, etc).**

2010 Fermi Symposium
9 – 12 May 2011
Rome Italy